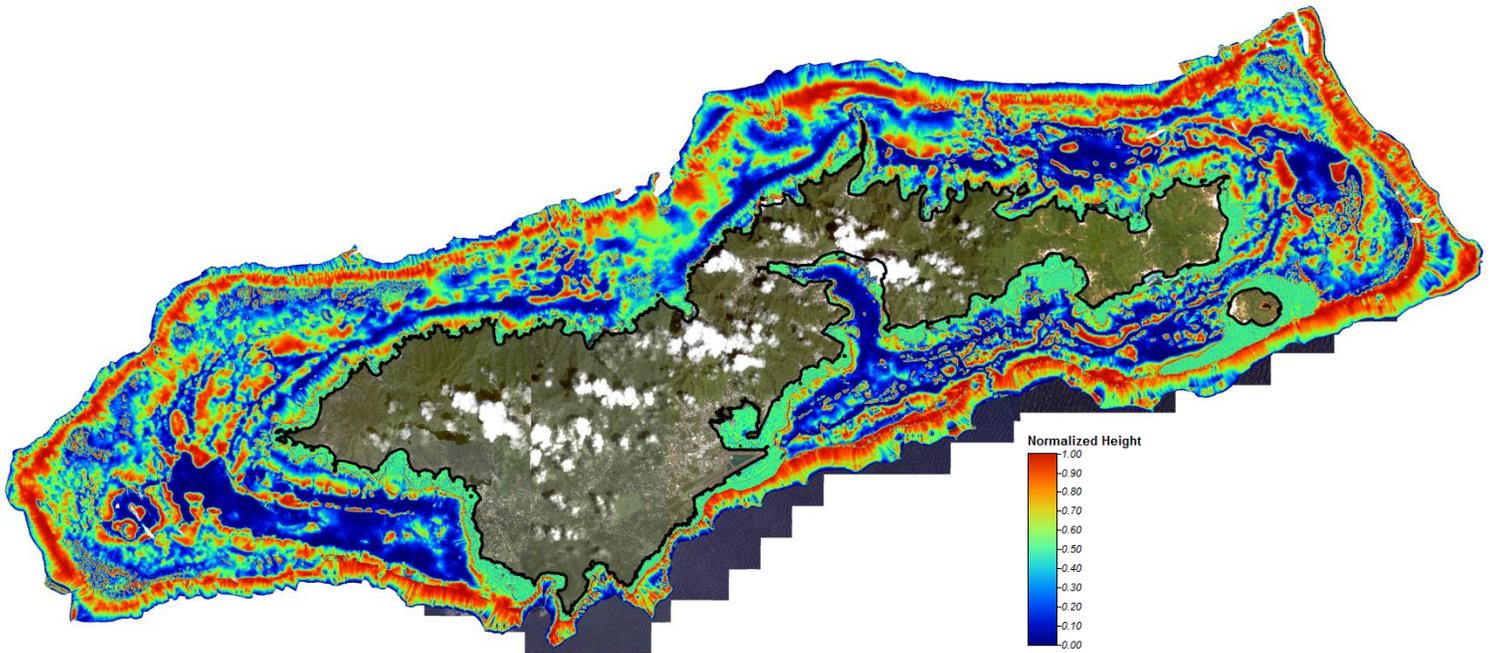


Terrain Metrics and Landscape Characterization from Bathymetric Data: SAGA GIS Methods and Command Sequences



On the Cover:

Ikonos mosaic sourced from: <https://data.noaa.gov/dataset/tutuila-island-ikonos-imagery-ikonos-imagery-for-american-samoa16efa>

SAGA GIS Normalized Height derived from merged Ikonos and multibeam bathymetry
http://www.soest.hawaii.edu/pibhmc/pibhmc_amsamoa_tutuila_bathy.htm

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Background

This document is a guide to the derivation of a variety of terrain metrics and descriptive measures of landscape composition. These metrics are to be used in support of the “Linkages” project, which is evaluating the relationship of terrain to fish and coral demographics in the Pacific region.

It is a “how to” document, providing command sequences, using the open source GIS software System for Automated Geoscientific Analyses (SAGA), to generate raster data layers of terrain metrics. SAGA was created, and is under continuous development by researchers at the Department of Physical Geography, Hamburg, Germany. It is distributed under the GNU General Public License (GPL), and is available for download from <http://sourceforge.net/projects/saga-gis/files/>. The project homepage is <http://www.saga-gis.org/en/index.html>.

Most, if not all of these metrics are available through other software packages. However, this would require the user to learn command sequences and processes for multiple software packages, as well as having to convert between different file formats. The use of SAGA is a more effective and efficient approach, by providing a comprehensive compilation of metrics, requiring only a single sequence for data import, and allowing the user to focus on the individual metrics of interest.

Organization

A brief description of the SAGA GUI is provided in the course of describing the steps to import CRED bathymetric data (in the ESRI ASCII grid file format, sourced from the PIBHMC site). In addition, sequences are provided to set the base GRID projection and coordinate system, as well as to EXPORT grids created in SAGA to the ESRI ASCII grid format. Users of this document are highly encouraged to review the SAGA User guides, Wiki and Library documentation, as well as a helpful tutorial can be found at the following URL:

http://live.osgeo.org/en/quickstart/saga_quickstart.html

These descriptions are followed by the command sequences necessary to generate the various metrics. The sequences are organized by module; include brief description of the metric, either taken from SAGA documentation or from a relevant reference, a graphic of the command hierarchy and definitions of dependent parameters where available. A list of references for further reading is provided at the end of the document. Example SAGA grid outputs from the sequences listed can be seen in the SAGA GIS Terrain Metrics and Classification Output.pptx PowerPoint presentation, which is a separate file.

General Description of SAGA GUI

This section provides a very brief introduction to the SAGA GUI. The reader is once again highly encouraged to review the User manuals and Wiki.

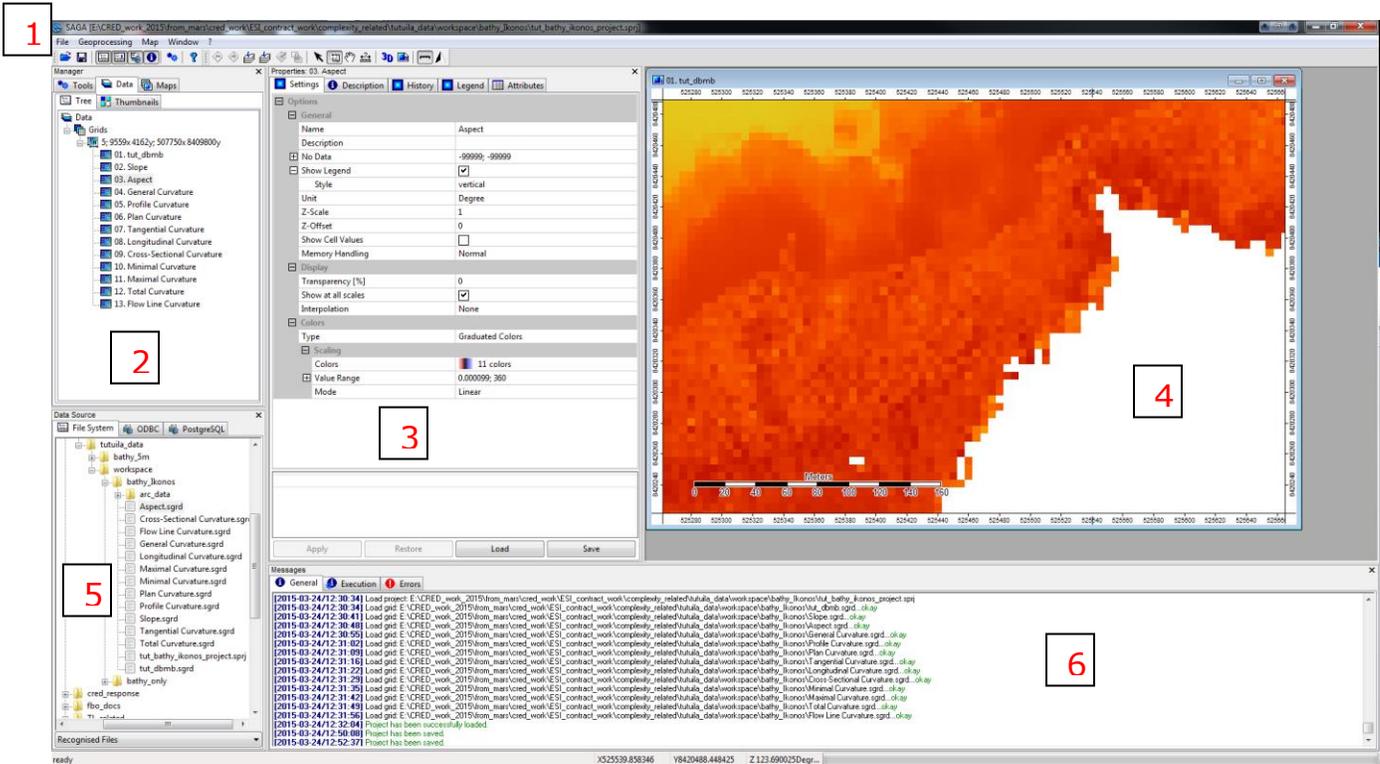


Figure 1: SAGA GUI

1. Menu bar – all command sequences that follow in this document are initiated here
2. Manager window – this lists the data layers in the project; context menus (right click) are available for data layers here
3. Object properties window – tabs above this window provide information specific to the selected data layer, as well as a description and listing of parameters/dependencies for any given module
4. Work area – map layers and various graphic output are displayed here
5. Data source – file system display
6. Messages – provides status of issued commands

Note: The User can navigate to specific tools in the Manager window, under the "Tools" tab; in the "Properties" window, the "Settings" tab shows the commands

and options in the metric command sequences, while the "Description" tab provides tool descriptions and supporting documentation

Description of Command Sequences

Sequences will take the form of a hierarchical tree. The section heading will describe the purpose of the sequence (e.g. "Set projection of Grid") and will include the module name where appropriate. The primary bubble is a command found on the Menu bar. Subsequent bubbles list the commands in order of execution. It is assumed that the user will select or "click" on the command, so this information is not repeated incessantly... Explanatory notes are provided under "Note:". Definitions/explanations of dependent parameters are provided where needed. It should be noted that the following tree is an exception as it describes the initial startup of SAGA and importation of data.

For each "Data Object = <create>", this will be the name of the output layer; e.g. "Normalized Height" = <create> will yield a normalized height data layer.

Start SAGA and Import ESRI ASCII Grid data

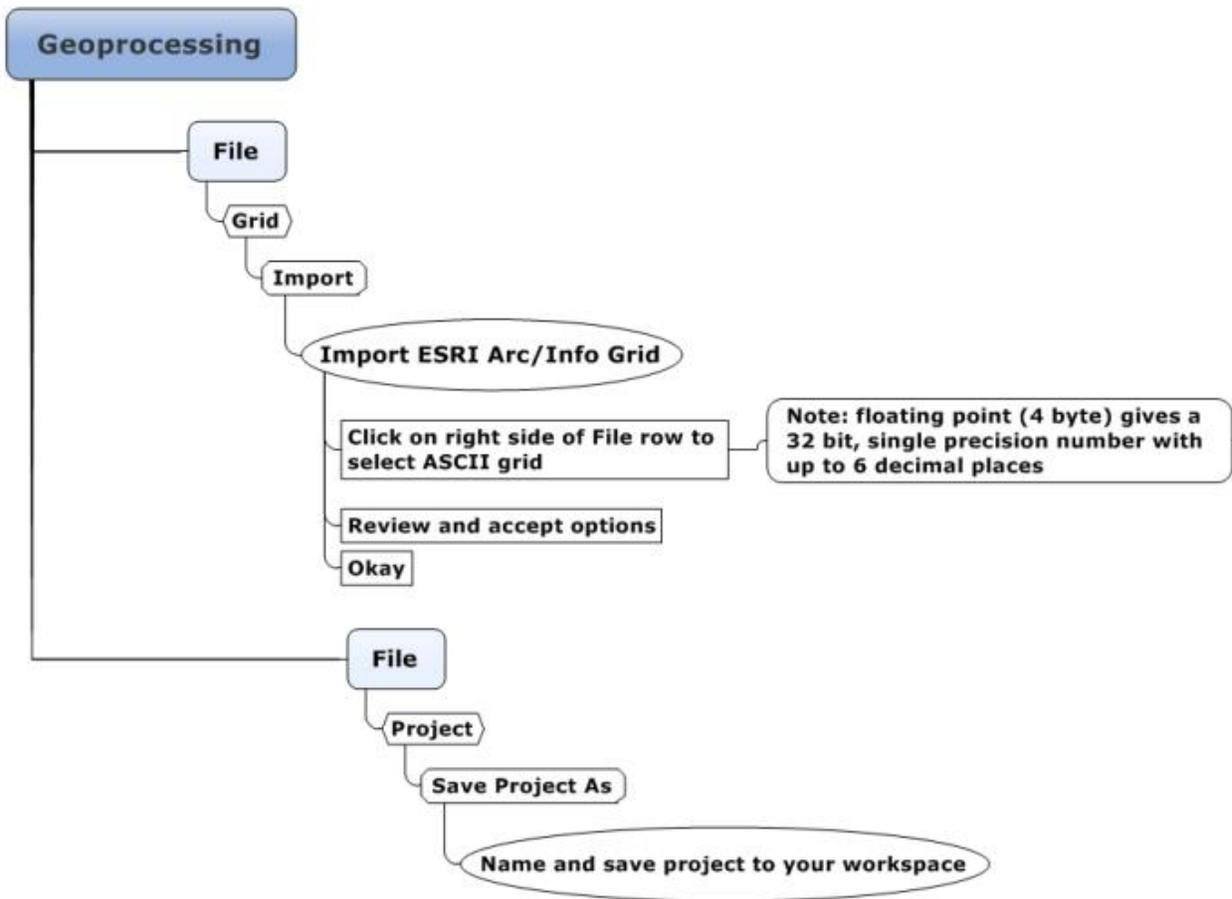


Figure 2: Start SAGA and import ESRI ASCII Grid data

Set Grid projection, coordinate system and datum

Note: the predefined projection file pibhmc_utm_projection.sprm was created using parameters found in the metadata associated with the Tutuila ASCII grid data. The sequence below describes how to create and save a projection file to define the projection for a given data layer.

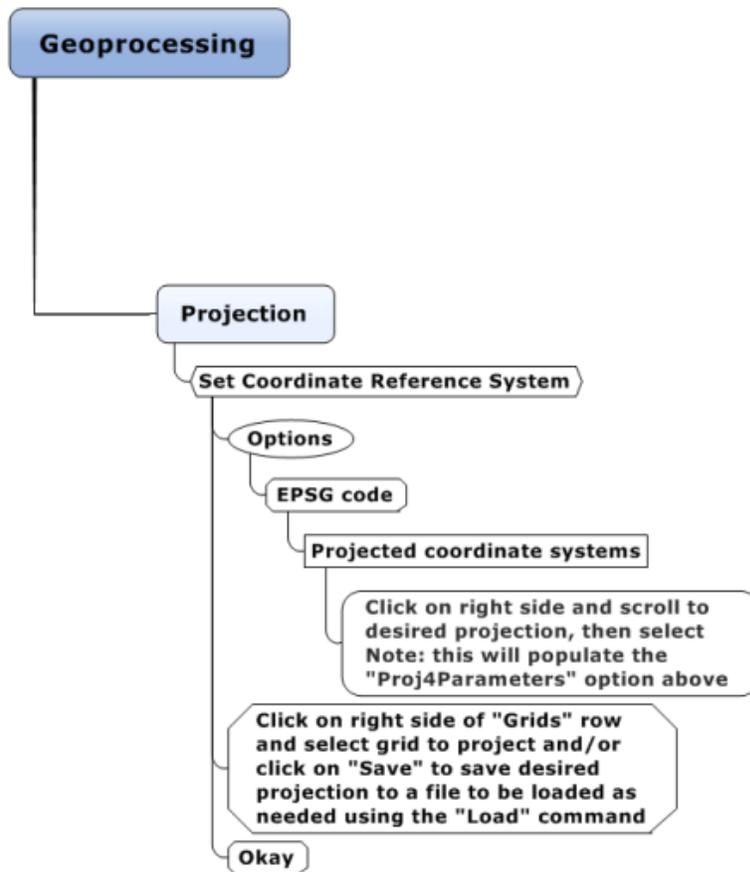


Figure 3: Set Grid projection, coordinate system and datum

Export SAGA grid to ESRI ASCII grid format

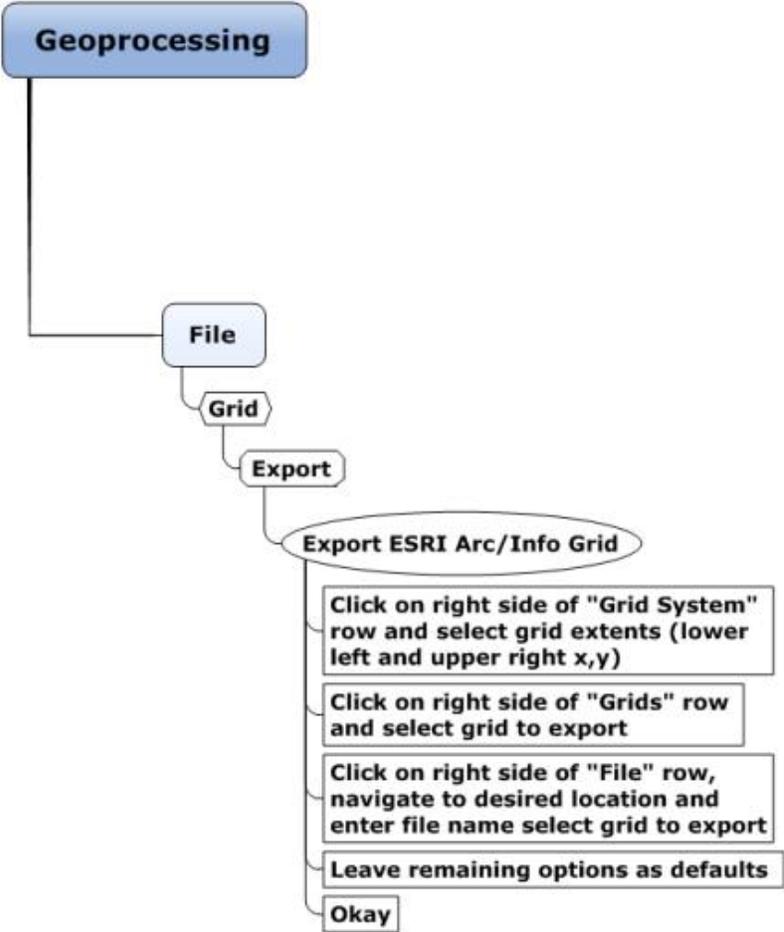


Figure 4: Export SAGA grid to ESRI ASCII grid format

TERRAIN METRIC SEQUENCES

Slope, Aspect and Curvature

Calculates the local morphometric terrain parameters slope, aspect and if supported by the chosen method also the curvature. Besides tangential curvature also its horizontal and vertical components (i.e. plan and profile curvature) can be calculated. (SAGA GIS Tool Description)

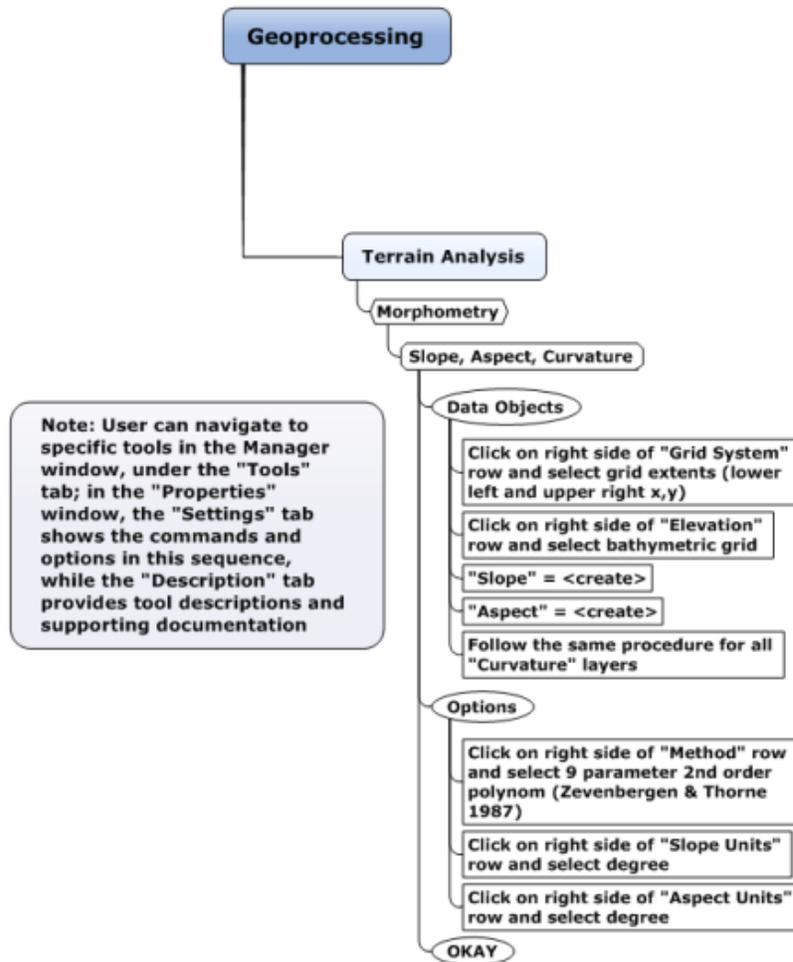


Figure 5: Slope, Aspect and Curvature

Convergence Index

Calculates an index of convergence/divergence [with] regard[ing] to overland flow. By its meaning it is similar to plan or horizontal curvature, but gives much smoother results. The calculation uses the aspects [or gradient] of surrounding cells, i.e. it looks to which degree surrounding cells point to the center cell. The result is given as [a] percentage[s], negative values correspond to convergent, positive to divergent flow conditions. Minus 100 would be like a peak of a cone, plus 100 a pit, and 0 an even slope.

(http://docs.qgis.org/2.6/en/docs/user_manual/processing_algs/saga/terrain_analysis_morphometry/convergenceindex.html)

Convergence index is useful for analysis of lineaments especially represented by ridges or channel systems as well as valley recognition tool

(<https://svn.osgeo.org/grass/grass-addons/grass7/raster/r.convergence/r.convergence.html>)

Suggested approach: There are two choices for convergence index. The version described here uses a window or filter – either 2x2 or 3x3 cells. For the way that Kelvin is analyzing the results, a 3x3 window is appropriate. There is also a version that uses a search radius, and allows for weighting, such as IDW, e.g. the farther a cell is away from the center, the less influence it has with re: to convergence or divergence. Gradient is the best “default” option, where just slope angle is the driver. Aspect might be useful if there were some sort of landscape scale directional trend (e.g. a dip or sloping trend in one direction). Gradient refers to steepness of slope; aspect is cardinal direction that the slope faces.

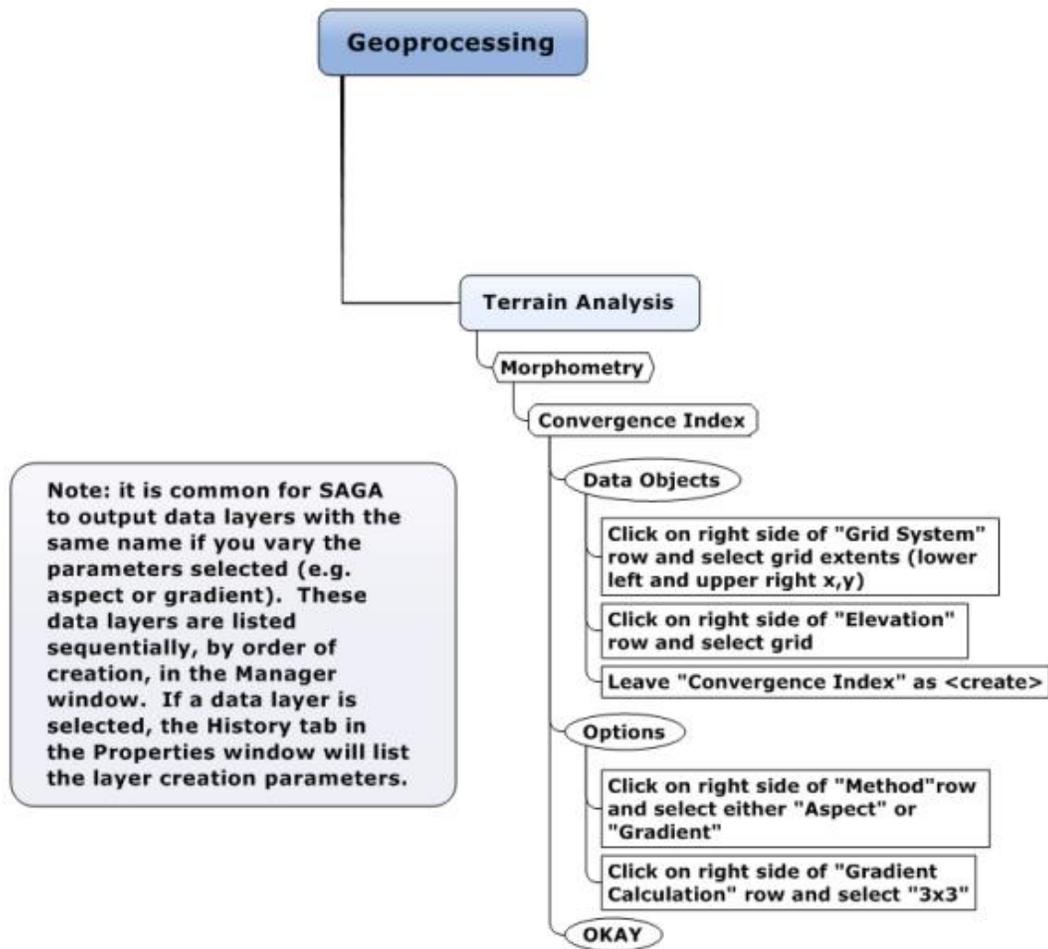


Figure 6: Convergence Index

Morphometric Protection Index

SAGA output for this module is "Protection Index".

This algorithm analyses the immediate surroundings of each cell up to a given distance and evaluates how the relief protects it. It is equivalent to the positive openness described in Yokoyama, R., et al. (2002).

Openness is an angular measure of the relation between surface relief and horizontal distance. It resembles digital images of shaded relief or slope angle, but emphasizes dominant surface concavities and convexities. Openness has two viewer perspectives. Positive values, expressing openness above the surface, are high for convex forms, whereas negative values describe this attribute below the surface and are high for concave forms (Yokoyama, R., et al., 2002).

The value for any given cell is a function of a summary of surrounding cell values in 8 directions. This is a relative metric, providing a positive or negative index value based on the values of the surrounding cells.

The index is a mean value, so those cells with no data are (or at least should be) accounted for by dividing the sum value by eight, even though there might only be data for 5 cells... this is not explicit, but is the proper calculation method.

The unit for the "radius" option is the native cell size, in this case equivalent to 5m. One hundred is the default value, and was used for the initial example data, not necessarily the optimal radius. The radius should be 15m for the first iteration of Kelvin's analysis, to match the 30m diameter cylinder around the sample point.

A detailed discussion of typical results from, and limitations of this metric are presented in Appendix 2.

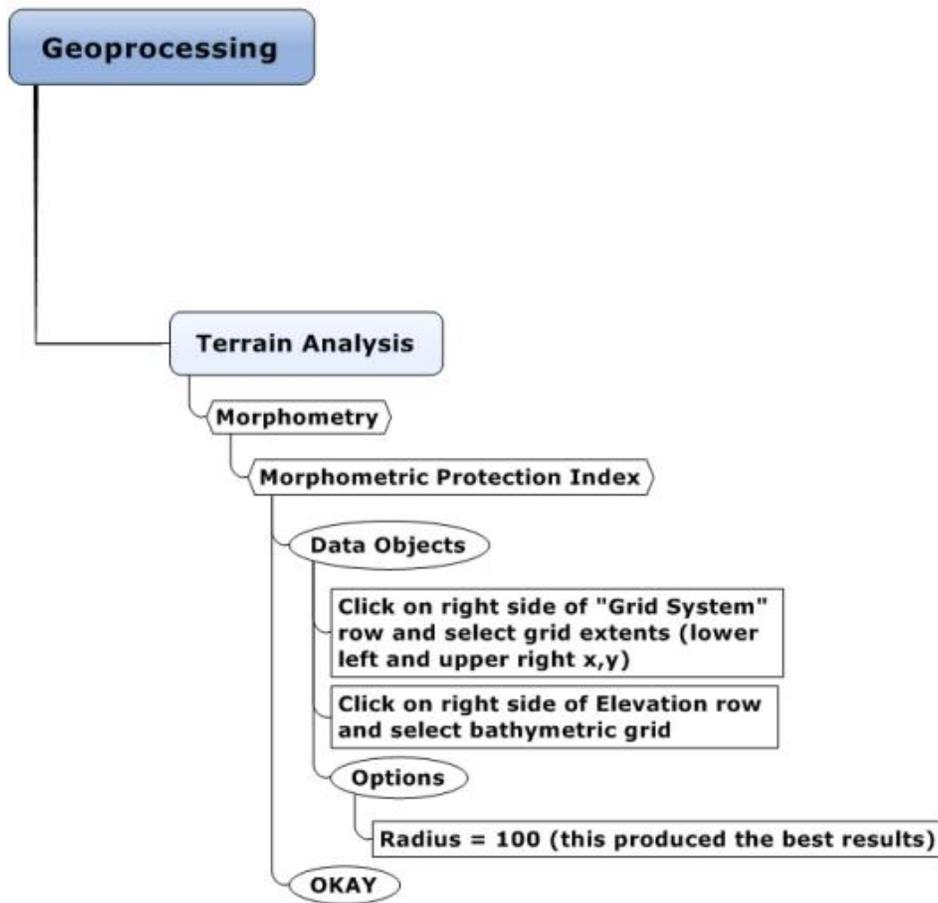


Figure 7: Morphometric Protection Index

Real Surface Area

Calculates real (not projected) cell area. (SAGA GIS). This is akin to rugosity, in that it takes into account texture (i.e. the “ups and downs” within each cell) as well as cell size. As the value increases, surface texture, or roughness, increases (Grohmann, C.h., et al., 2009). The actual algorithm for calculation in SAGA is not documented.

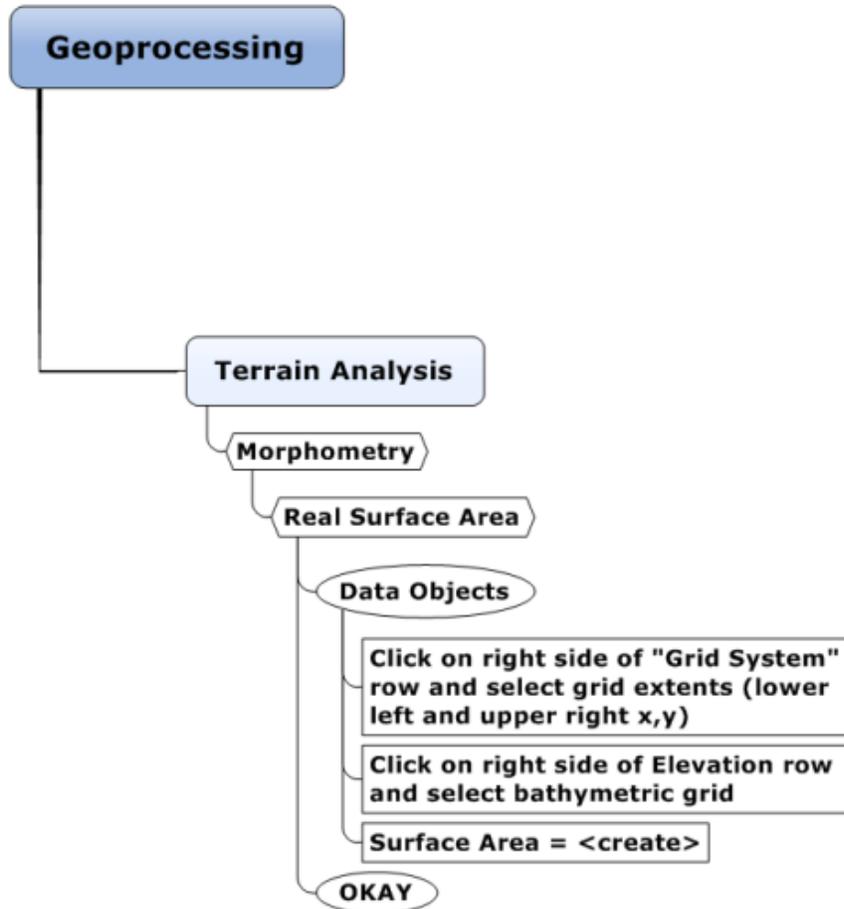


Figure 8: Real Surface Area

Terrain Ruggedness Index (TRI)

Riley et al. (1999) describe this as *an objective quantitative measure of topographic heterogeneity... by calculating the sum change in elevation between a grid cell and its eight neighbor grid cells*. This tool works with absolute values by squaring the differences between the target and neighbor cells, then taking the square root. Concave and convex shape areas could have similar values.

The output from this tool can be grouped / classified in whatever scheme the user desires. That is the reason ESRI ASCII grids were generated, so that you could use what you are familiar with to see which patterns pop out. You'll also note that the most "rugged" terrain is found in the Ikonos data – this is questionable data, with a high degree of variance in cell values...

Options:

The radius of the moving window/filter can be set by the user, and that number will determine how many cells are used to calculate the change in elevation. For example, if the radius is set to 2, then 16 neighbor cells will be used in the calculation. The radius distance is equal to the sum of the number of cells specified (i.e. if the value is 2 and the cells are 5m, then the radius = 10m in actual distance)

Weighting Function: 4 parameters available (no distance weighting, inverse distance to a power, exponential, Gaussian weighting)

No weighting parameters were used in generating the example data set.

Finally, it should be noted that the value of this metric will vary as a function of the size and complexity of the terrain used in the analysis.

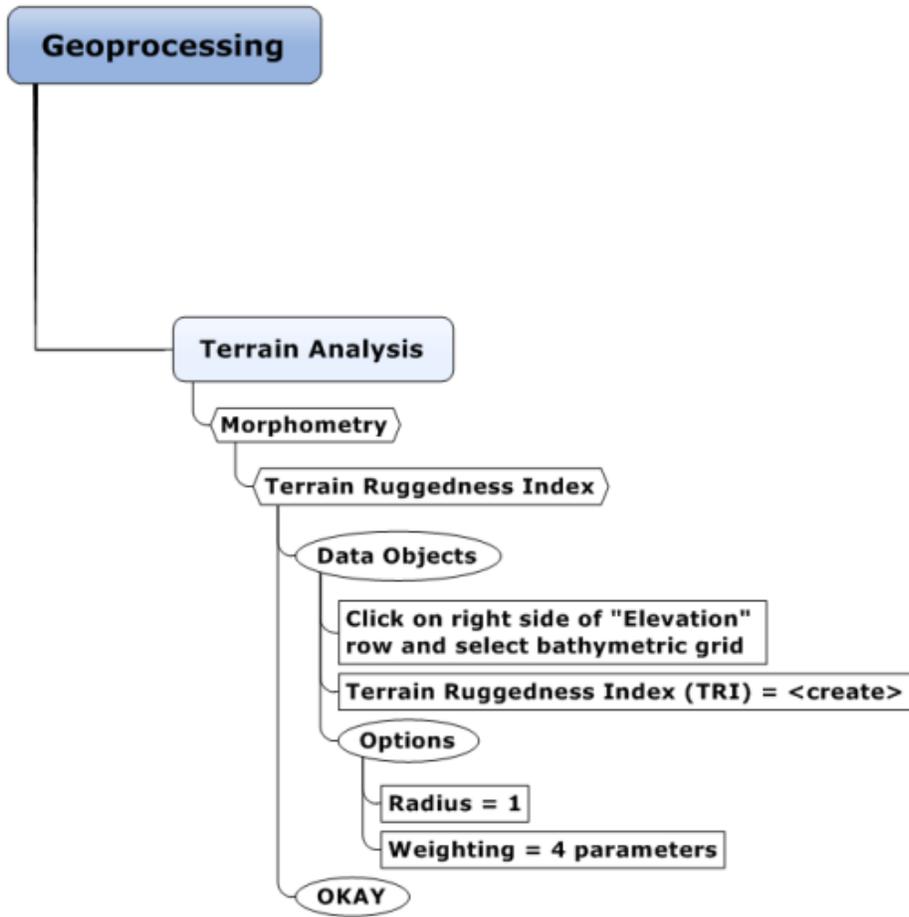


Figure 9: Terrain Ruggedness Index (TRI)

Terrain Surface Convexity

Terrain surface convexity as proposed by Iwahashi and Pike (2007) for subsequent terrain classification (SAGA GIS).

Convexity has been described as *positive surface curvature...yielding positive values in convex-upward areas, negative values in concave areas, and zero on planar slopes*. Each grid cell value represents *the percentage of convex-upward cells within a constant radius of ten cells* (Iwahashi and Pike, 2007. pp.413-414). Each cell is compared to all other cells within the constant radius window.

It should be noted that this metric is similar in nature to the Convergence and Morphometric Protection indices. The differences lie in the method used for calculation. Also, the percentage calculated is based on the number of cells within the specified radius (10 for the sample data), and may not necessarily sum to 100.

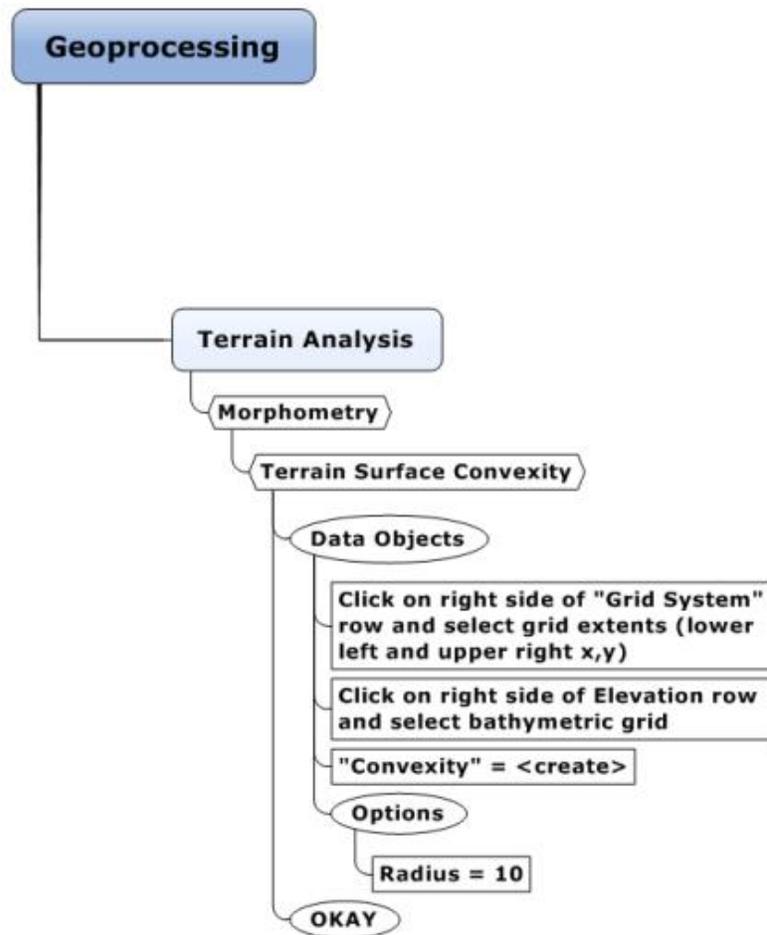


Figure 10: Terrain Surface Convexity

Terrain Surface Texture

Terrain surface texture as proposed by Iwahashi and Pike (2007) for subsequent terrain classification (SAGA GIS).

This parameter emphasizes fine versus coarse expression of topographic spacing, or "grain"... *Texture is calculated by extracting grid cells (here, informally, "pits" and "peaks") that outline the distribution of valleys and ridges.* It is defined by both relief (*feature frequency*) and *spacing* in the horizontal. Each grid cell value represents the relative frequency (in percent) of *the number of pits and peaks within a radius of ten cells* (Iwahashi and Pike, 2007. pp.412-413).

It should be noted that it is not clear that the relative frequency is actually a percentage. According to Iwahashi and Pike (2007, p.30), *To ensure statistically robust classes, thresholds for subdividing the images are arbitrarily set at mean values of frequency distributions of the input variables.*

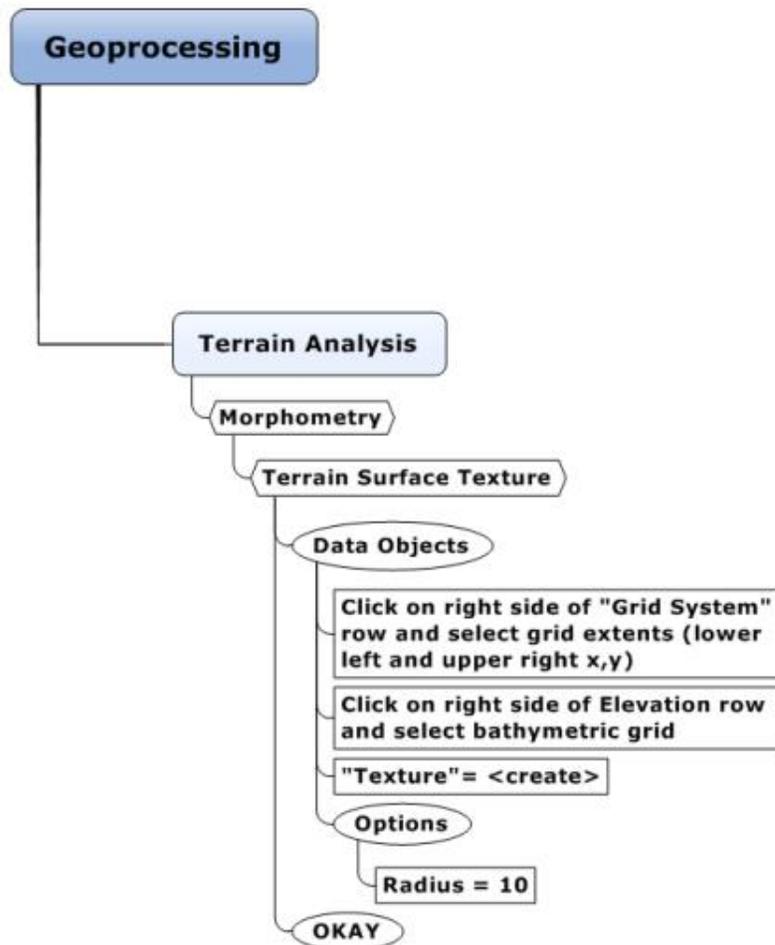


Figure 11: Terrain Surface Texture

Topographic Position Index

Topographic Position Index (TPI) calculation as proposed by Guisan et al. (1999). This is literally the same as the difference to the mean calculation (residual analysis) proposed by Wilson and Gallant (2000). The bandwidth parameter for distance weighting is given as percentage of the (outer) radius.

Weiss (2000) provides a very good description of the topographic position index (TPI), and methods to derive a landscape classification from these values. The TPI algorithm compares a DEM cell value to the mean value of its neighbors. The mean value is calculated based on the shape selected by the user. Positive values represent features typically higher than surrounding features, negative values represent lower features, and values near zero are either flat or areas of constant slope.

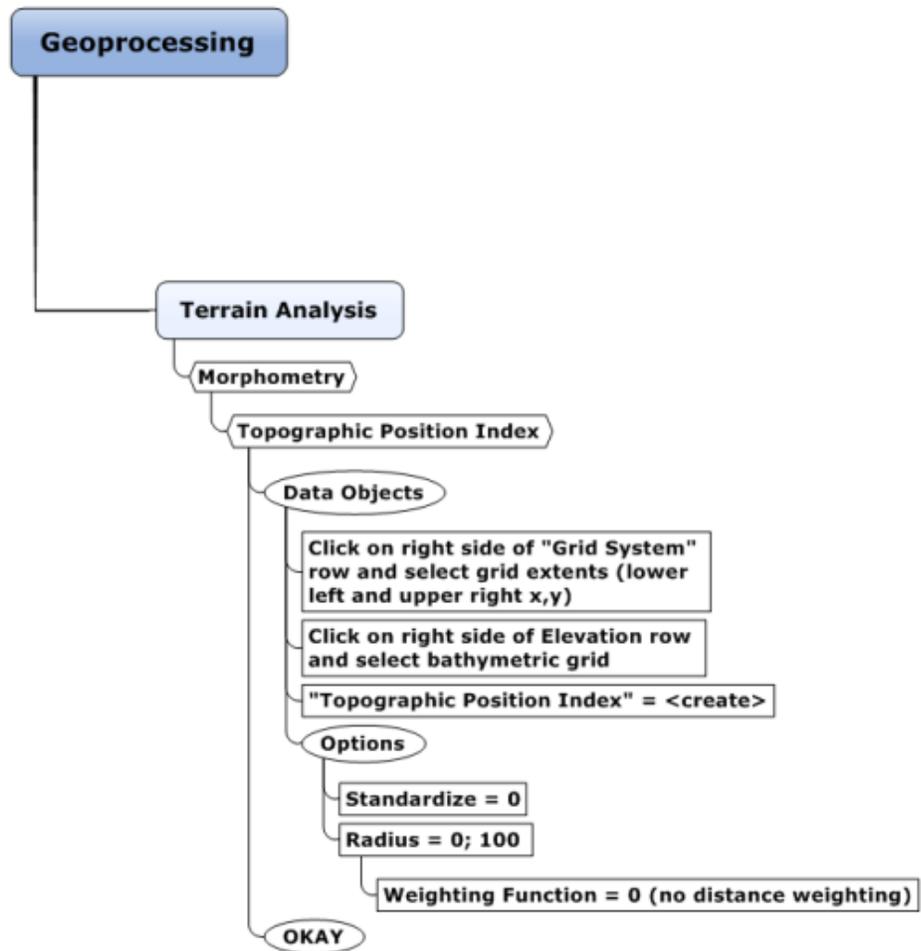


Figure 12: Topographic Position Index

TERRAIN CLASSIFICATION SEQUENCES

Note: the representations of terrain classifications provided as a supplement to this report take one of several possible forms. They are primarily continuous, but the user can create numeric or (e.g. 1.5 – 1.9) or categorical schemes (e.g. slope, ridge) by thresholding the continuous or discrete landscape values.

Fuzzy Landform Element Classification

Algorithm for derivation of form elements according to slope, maximum curvature, minimum curvature, profile curvature, tangential curvature, based on a linear semantic import model for slope and curvature and a fuzzy classification Based on the AML script 'felementf' by Jochen Schmidt, Landcare Research (SAGA GIS Tool Description).

In simpler terms, this module uses slope, aspect and four measures of slope curvature (minimum, maximum, plan and tangential) as inputs to an unsupervised classification method (e.g. ISODATA, or k-means) to categorize terrain into natural landform groupings (Irvin, et al., 1997; Petry, F., et al., eds., 2010). It also calculates the relative uncertainty in the classification by describing how well a specific grid cell and its associated terrain features fit within a given terrain class. This is represented by the Maximum Membership, Entropy and Confusion Index data layers and values.

Note: this module requires Slope, Minimum, Maximum, Profile and Tangential curvature grids as inputs. Irvin et al., 1997, describe these as “five principal attributes” commonly used to describe landforms.

Options

Slope Grid Units: degree (default)

Slope Threshold: 5:15 (default)

It should be noted that this means the planar area is less than 5 degrees (probslope=0) and slope area (probslope=1) is more than 15 degrees, and values in between for this case yield a fraction between 0 and 1. For example, if the terrain slope = 7, then the probability of classification as “flat” is 0.8, and probability of classification as a slope is 0.2

Curvature Thresholds: 0.000002; 0.00005 (default)

It should be noted that these threshold values are labeled as “null” values, indicating a lack of curvature, i.e. flat or planar terrain. These thresholds are then used to calculate the probability that any given value falls within the vertical and horizontal curvature value ranges for the various classes of curvature (e.g. minimum, profile, etc.). The math is simple enough; the drivers are more the curvature characteristics of the terrain being studied. These thresholds will vary based on the type of terrain being characterized, and appropriate values for “coral-based” terrain need to be determined.

Default Classes:

Function of slope, maximum curvature, and minimum curvature

Plain (Classification Value = 100), Pit (Classification Value = 111), Peak (Classification Value = 122), Ridge (Classification Value = 120), Channel (Classification Value = 101), Saddle (Classification Value = 121)

Function of slope, profile curvature, tangent curvature

Back Slope (Classification Value = 0), Foot Slope (Classification Value = 10), Shoulder Slope (Classification Value = 20), Hollow (Classification Value = 1), Foot Hollow (Classification Value = 11), Shoulder Hollow (Classification Value = 21), Spur (Classification Value = 2), Foot Spur (Classification Value = 12), Shoulder Spur (Classification Value = 22)

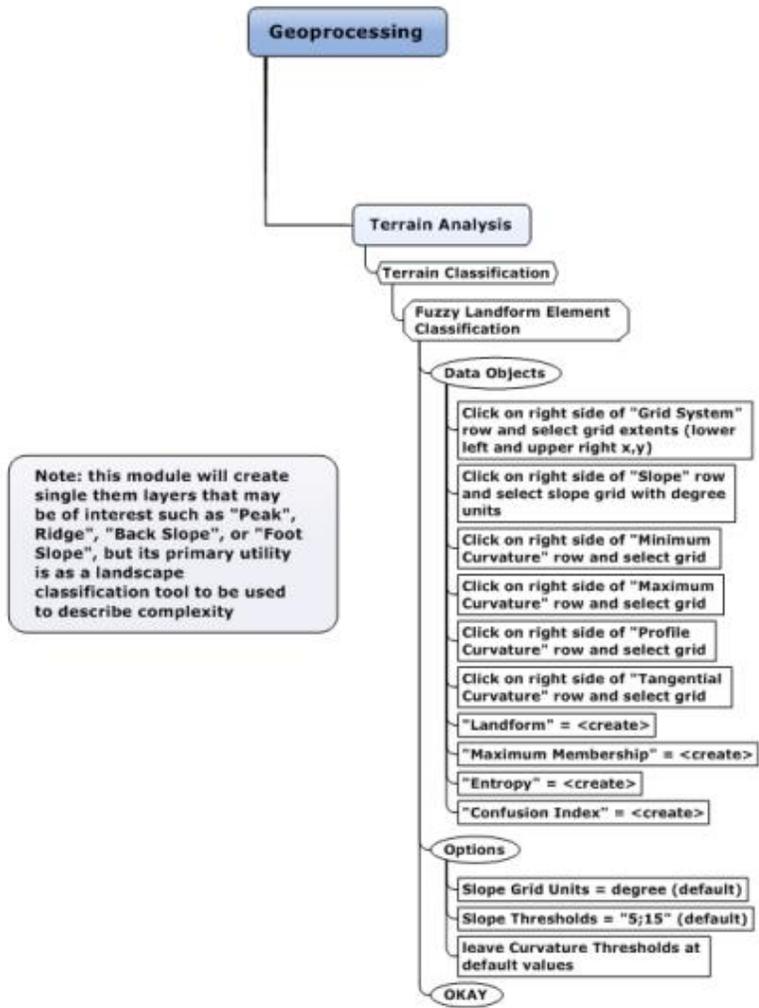


Figure 13: Fuzzy Landform Element Classification

Grid Pattern Analysis

This description is taken from de Smith, et al. (2015). *The input is a single image file and the output is again an image file, this time with each pixel representing the computed (i.e. transformed) value computed from the input image. Note that a kernel of pixels is used for each calculation, in this case selectable from 3x3, 5x5 or 7x7 pixel blocks. These operations are essentially pre-defined map algebra focal operations. The various texture measures that are supported are as follows:*

*Relative Richness: $R=n/n_{max}*100$, where n =the number of different classes present in the kernel, n_{max} =maximum number of classes in entire image*

Diversity: $H = -\sum(p\ln(p))$, where \sum =the sum over all classes in the entire image, and p =proportion of each class in the kernel*

Dominance: $D=H_{max}-H$, where H =Diversity, H_{max} =maximum diversity= $\ln(n)$ and n =number of different classes present in the kernel

Fragmentation: $F=(n-1)/(c-1)$ where n =number of different classes present in the kernel, c =number of cells considered (9, 25 or 49)

NDC=number of different classes in each 3 x 3, 5 x 5, or 7 x 7 neighborhood (ranges from 1-9, 1-25, 1-49)

CVN=number of cells different from the center cell in each 3x3, 5x5, or 7x7 neighborhood (ranges from 0-8, 0-24, 0-48)

The Diversity and Center v. Neighbor (CVN) metrics are promising for the Linkages analysis as they will provide an indication of the complexity and variability of terrain within the 30m areas of interest.

Notes:

The input "Landforms" is the output of the "Terrain Surface Classification". Also, this reference, de Smith, et al. (2015) is an excellent resource for geospatial analysis.

Options

Size of Analysis Window: 5x5

Max. Number of Classes: 12

This is the actual number of classes in the data layer, but needs to be specified by the user, as SAGA does not automatically detect the number of classes.

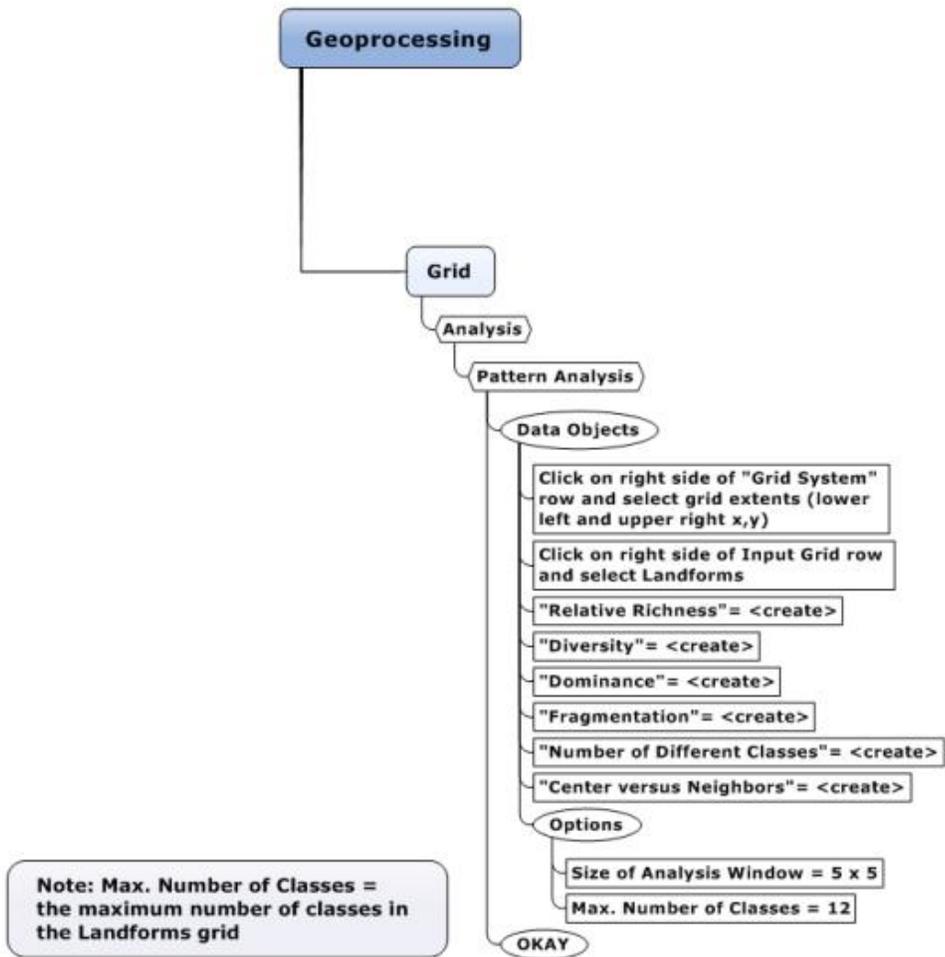


Figure 14: Grid Pattern Analysis

Surface Specific Points

Peucker and Douglas (1975) are cited as the reference to describe how this module works. Unfortunately, this is a very difficult publication to obtain. These are considered the "high information" points, and can be captured by interpolation according to the following: *An effective strategy is to start at the low point on a stream or ridge, and to continue up until the high point is reached. Saddle points, summits, and pits (depressions) are then places where the stream and ridge lines converge. Algorithms exist to detect these features in grids, and to vectorize the features for use in GIS[s] (Clarke, 1995, p.257).*

The SAGA output is named "Result", and grid cell values are determined by height and slope of adjacent terrain cells. The possible range of values is -1 (negative) to +1 (positive).

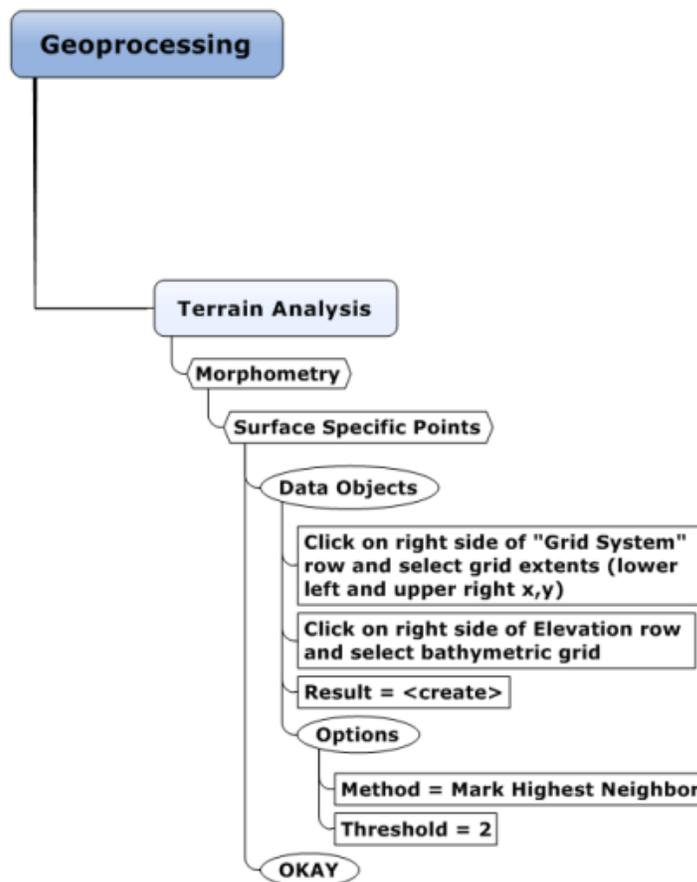


Figure 15: Surface Specific Points

Terrain Surface Classification

Terrain surface classification as proposed by Iwahashi & Pike (2007). This module derives a classification of the landscape based on slope, convexity and texture. Not surprisingly, required inputs are: Slope, Convexity and Texture. The output grid is Landforms. The user can select a classification based on 8, 12 or 16 landscape categories.

It should be noted that this classification scheme is based on relative metrics, so while a coarse scale analysis with lots of variation may yield a more dramatic classification, at the island scale this tool may still yield something useful. All of these metrics and classifications require user review and input to extract a useful and representative classification scheme.

Slope is the first measure to be used in the classification, followed by Convexity and Texture.

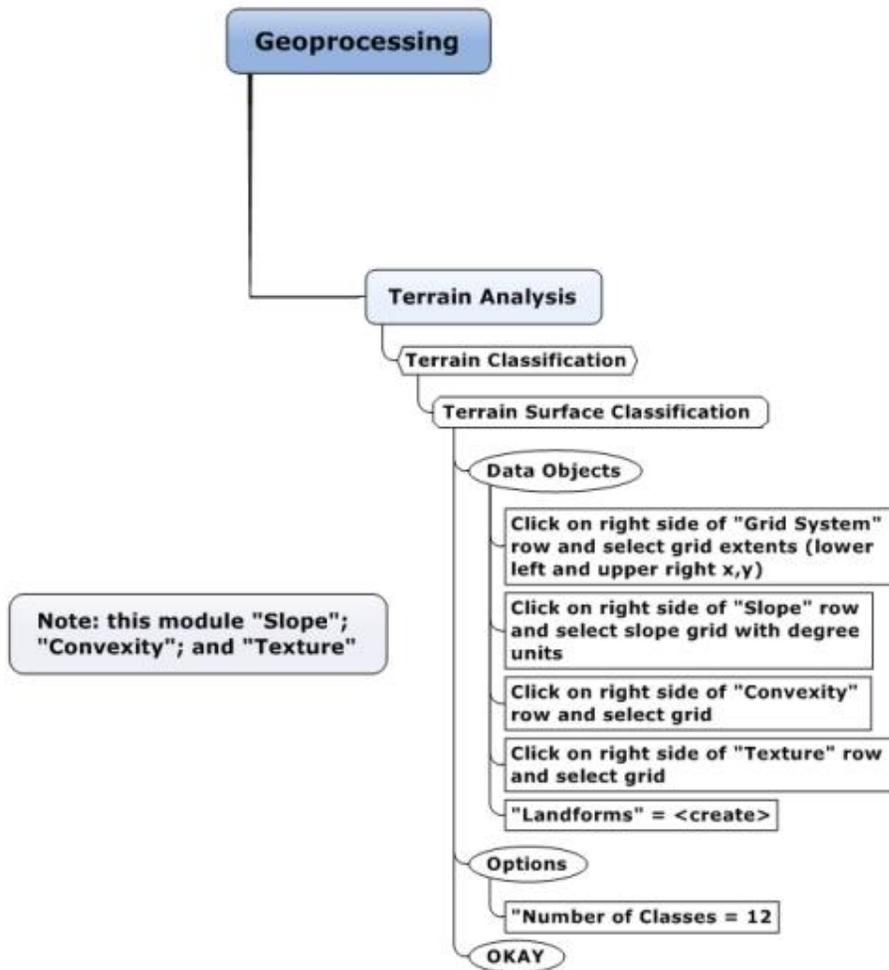


Figure 16: Terrain Surface Classification

TPI Based Landform Classification

Topographic Position Index (TPI) calculation as proposed by Guisan et al. (1999). This is literally the same as the difference to the mean calculation (residual analysis) proposed by Wilson and Gallant (2000). The bandwidth parameter for distance weighting is given as percentage of the (outer) radius.

Weiss (2000) provides a very good description of the topographic position index (TPI), and methods to derive a landscape classification from these values. The TPI algorithm compares a DEM cell value to the mean value of its neighbors. The mean value is calculated based on the shape selected by the user. Positive values represent features typically higher than surrounding features, negative values represent lower features, and values near zero are either flat or areas of constant slope.

Ranges of TPI values can be used to generate a terrain classification or categorization of features and landforms within a landscape. The sequence below derives one such landscape classification. It is important to remember that the TPI is scale dependent; meaning the size and shape of the focal area chosen to calculate the initial values may highlight or ignore important landscape features. In addition, the output is numeric only, so if desired, the user will need to assign a categorical classification (e.g. backslope, foreslope, etc.)

Options

Radius = 0; 100

Radius = 0; 100

The first radius is the overall radius of the moving window. The second radius allows for a continuous focal window (like a circle) or something different (like a donut). See figure 2a in Weiss (2000).

Class Description Breakpoints

1 ridge > + 1 STDEV

2 upper slope > 0.5 STDV =< 1 STDV

3 middle slope > -0.5 STDV, < 0.5 STDV, slope > 5 deg

4 flats slope >= -0.5 STDV, =< 0.5 STDV, slope <= 5 deg

5 lower slopes >= -1.0 STDEV, < 0.5 STDV

6 valleys < -1.0 STDV

Weiss (2000) provides an example of a class definition scheme. It is unclear if this scheme has been adopted and implemented in SAGA. In any case, categories and thresholds are terrain-dependent and should be defined based on user needs.

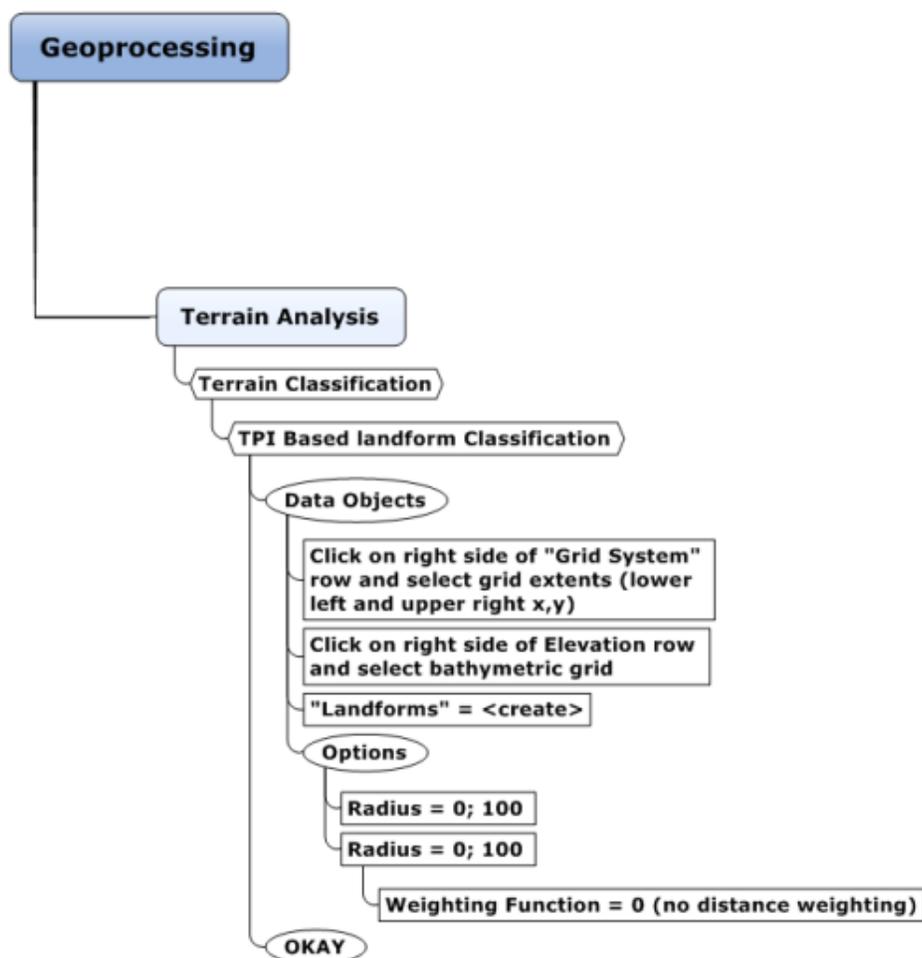


Figure 17: TPI Based Landform Classification

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Appendix 1: Metrics and Terrain Classification Options Reviewed but Not Selected

Landscape Metrics

Curvature Classification – the only available documentation is in German. See Dikau, R. (1988)

Diurnal Anisotropic Heating - not a structural metric - addresses diurnal heat balance as influenced by topography... See Hengl, T. and R. Hannes, eds. (2009)

Downslope Distance Gradient – not a structural metric - this is a hydrologic measure of the impact of local slope characteristics (e.g. convex or concave) on the hydraulics gradient. See Hjerdt, et. al, (2004)

Relative Heights and Mid-Slope Positions

I'm not sure that this is a meaningful metric for our purposes. If we were looking for a good place to put a vineyard, this would be very useful though.

Dietrich and Böhner (2008) provide the following explanations: *Normalised height allots value 1 to the highest and value 0 to the lowest position within a respective reference area. Standardised height is the product of normalised height multiplied with absolute height; Mid-slope position assigns mid-slope positions with 0, whereas maximum vertical distances to the mid-slope in both valley or crest directions are assigned with 1* (p.42).

In addition, some clarification of the parameters is provided at the following URL: <http://sourceforge.net/p/saga-gis/discussion/790705/thread/c57eb4aa/?limit=25>

If you are having trouble sleeping, more explanation is provided in Böhner, J., and Selige, T., (2006) in a very dense manner.

The “reference area” is the catchment or landscape, and is an influencing factor, as the heights are relative to each other within the limits of the landscape or reference area. One of several \$64k questions – i.e. what is the appropriate scale of analysis. From a landscape perspective it depends on the scale and pattern of spatial variation of the feature of interest (i.e. topography, soils, vegetation). From a fisheries perspective, I'm thinking something like the home range of the single species of interest, or an average of multiple species... this is a good question for the fish team!

I can try to (maybe) explain the parameters a bit more just for background:
"w" = the larger the catchment/reference area/landscape, the smaller the influence is of any particularly high elevation

"e" = influences the position of any particular elevation by accounting for the slope angle

"t" = determines the amount of influence the highest elevation value in a window has on the relative height calculation

<http://sourceforge.net/p/saga-gis/discussion/790705/thread/c57eb4aa/?limit=25>

According to the forum URL above,

w: weights the influence of catchment size on relative elevation (inversely proportional)

e: controls the position of relative height maxima as a function of inclination

t: controls the amount by which a max. in the neighborhood of a cell is taken over into the cell (smaller the t, the smoother the result)

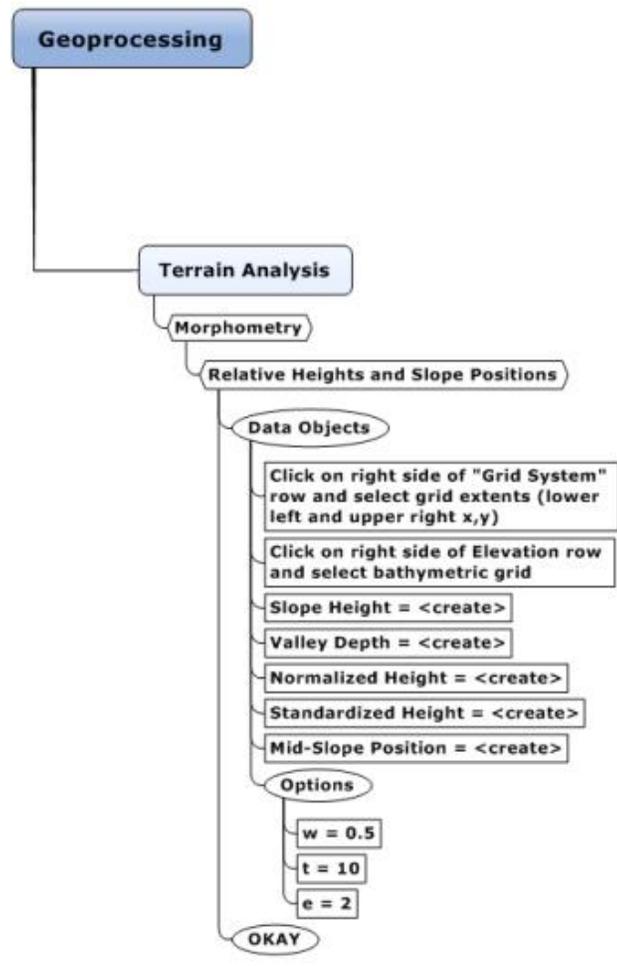


Figure 18: Relative Heights and Slope Positions

Terrain Classification

Fragmentation (Standard and Alternative), found under Grid => Analysis – this module produces density (identifies interior and exterior/edge patches), connectivity (indicates connectivity between patches) and fragmentation data layers using the standard “moving window” approach. These layers are typical outputs for a fragmentation analysis. The issue with the SAGA implementation is that only a single class can be analyzed per iteration. Therefore with the Tutuila pilot data, which is a 12-class data layer, this analysis would have to be run 12 separate times and then merged in some fashion and interpolated. This is not a scientifically sound or feasible approach.

Patch Analyst – this is an implementation of the Fragstats software within the ArcGIS environment. Modules that operate on polygons and grids are available. Classification data layers can be analyzed at the landscape and patch scale. The “Landforms” layer, created using the procedure outlined under Terrain Surface Classification (p.25 of this document) was reclassified using the “Name” attribute, to “Class_1” through “Class_12”. Class number increased as the default value ranges increased. It should be noted that the reclassification could be more meaningful if expert knowledge were applied to interpolate the classification. This data layer was then exported to the ESRI ASCII Grid format, imported to ArcGIS as a raster grid, then converted to polygons. The “Spatial Statistics” option under “Patch Analyst” was used to generate both landscape and patch scale metrics. Outputs are both tabular and thematic, with the majority of the output contained in the table, where one value characterizes the landscape or the universe of classes (e.g. Patch Density & Size Metrics, Edge Metrics, Shape Metrics, Diversity Metrics). Thematic outputs are a data layer with Mean Shape Index, Mean Perimeter-Area Ratio, and Mean Patch Fractal Dimension attributes associated with each polygon.

For the Linkages analysis, a single index value describing landscape or patch assemblage characteristics has very little value, unless perhaps an island scale analysis is undertaken (e.g. total fish biomass for a island A, related to the entire landscape metric , compared to the same variables for island B). In addition, it is not clear what value the thematic metrics might have with regard to fish demographics.

Appendix 2: Evaluation of "No Data" areas and Morphometric Protection Index

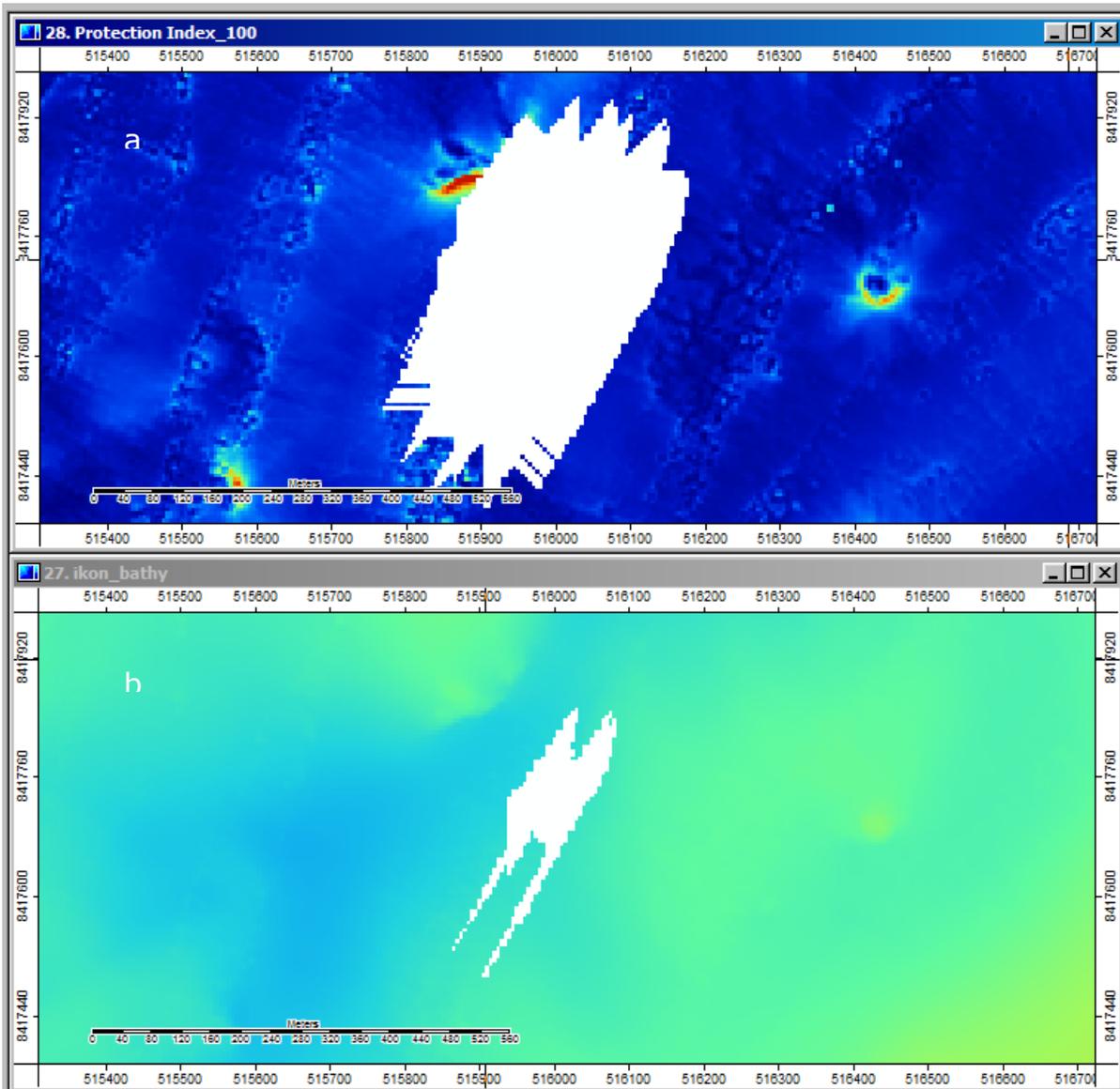


Figure 19: a) SAGA-generated "No data" area; b) bathymetry "No data" area

This is a comparison of no data areas in the original input bathy file (b) and the morphometric protection index with a 100 cell radius (a). The width of the "no data" area in the original is approximately 95 cells at its widest point, while the protection index is approximately 275 cells.

Measurements were not exact, but show general agreement, i.e. taken from the center pixel of the input the output should be approximately 286 cells in width ($95/2 = 42.5$ (43); $43 + 100 = 143$; $143 * 2 = 286$).

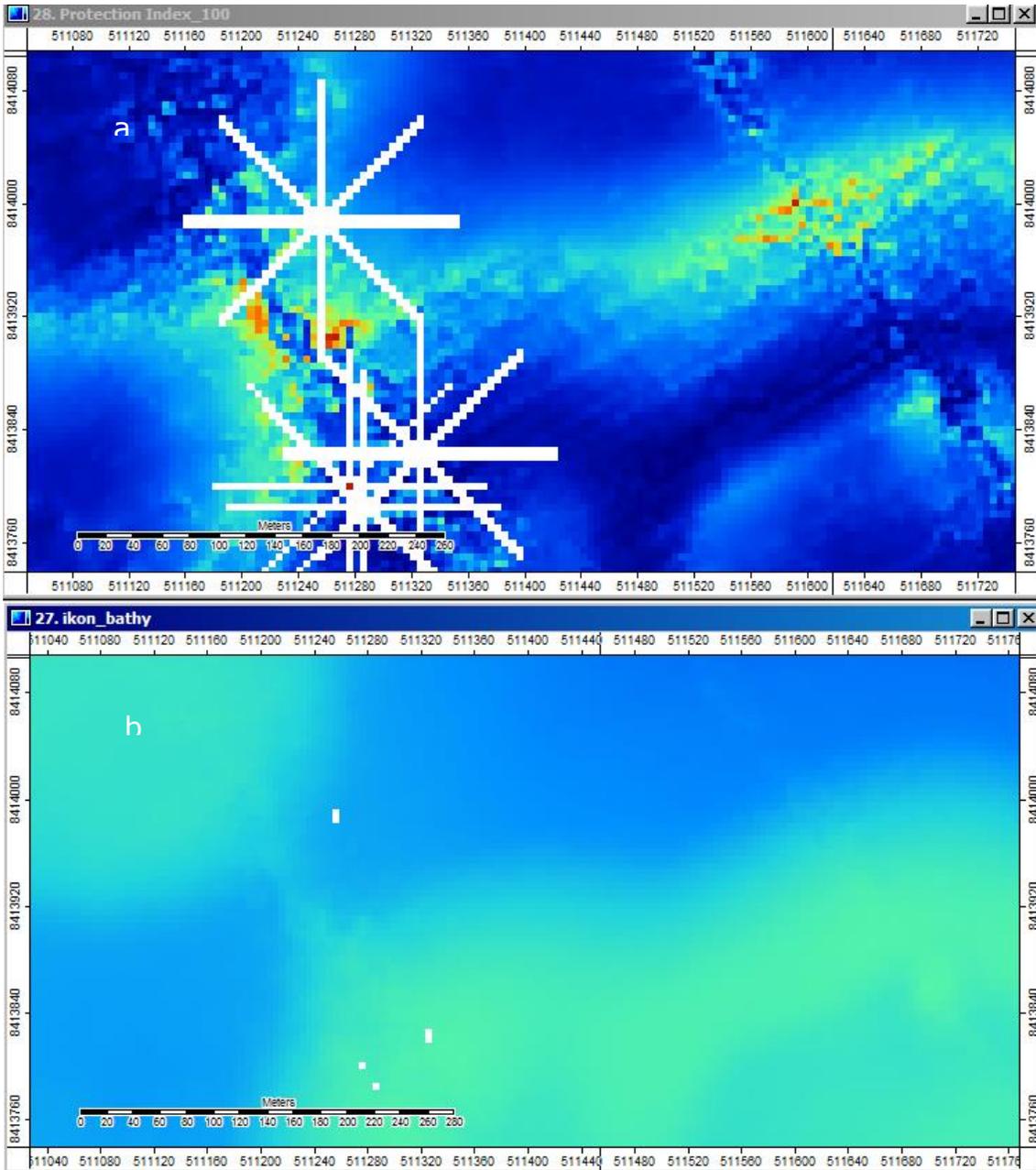


Figure 20: a) SAGA-generated artifacts; b) bathymetry “No data” areas

This graphic illustrates the original bathy with small “no data” gaps and the MPI output with odd star-shaped patterns. It is reasonable to expect this to be a no data blob with a 100 cell radius. Instead we have a star with 100 cell legs... The layer created using a 200 cell radius (not shown here) displays the same relationships.

However, in Yokoyama, et al., 2002, the angular change in elevation is calculated in a similar pattern to what we are seeing. I have to confess that while I

understand the concept, I don't completely understand the implementation... What we are seeing is what I would call an "artifact". Sometimes this raster processing business generates odd results.

As you are looking at the data, you are seeing issues of data quality that are not unexpected. Based on this result alone, I would recommend that you take the original merged multibeam/Ikonos bathy grid and run a majority filter over it to fill in no data gaps such as those shown above. The decision rule for you is how big to make the majority window. For example, the two rectangles shown in the image above are 5 x 10 cell data gaps.